Beachrock in the Hawaiian Islands[1]

K. O. Emery and Doak C. Cox[2]

Beachrock is a stratified calcareous sandstone (calcarenite) or conglomerate (calcirudite) occurring along many beaches that are composed of shells or other calcareous debris. It is common on beaches of islands that are bordered by coral reefs. Although many authors have described beachrock, few have agreed on its origin, either because critical data are lacking or because beachrock may form in several different ways. Preliminary studies of beachrock in the Marshall, Mariana, and Hawaiian Islands led the authors to believe that detailed mapping of beachrock in the Hawaiian Islands might show whether the distribution is related to abundance and composition of ground water or to other factors of the shore environment.

Examination of the shores of Oahu, Kauai, Molokai, and Maui during parts of June and July, 1954, was made possible by funds from Office of Naval Research contract NR 081–217.

Aid in field mapping, discussion, and critical reading of the manuscript was kindly given by Dr. Douglas Inman of Scripps Institution of Oceanography. Dr. Harold S. Palmer of Honolulu also read the manuscript and made some valuable suggestions.

GENERAL DESCRIPTION

Composition

The material that becomes cemented into beachrock is beach sand or gravel, chiefly calcareous. The sand ranges from fine to very coarse and, like other beach sands, is very well sorted (Table 1). Its generally coarse grain size, excellent sorting, and high degree of rounding, make it very permeable. Tests on progressively coarser Oahu samples 14, 2, and 4 of Table 1, yielded permeabilities of 37, 120, and 570 darcys, respectively, values that are comparable with those of other beach sands.

The grains of sand consist chiefly of broken and worn pieces of calcareous parts of organisms, plus minor amounts of volcanic detritus. Volcanic detritus is unusually abundant in beachrock at Ohikilolo (about 2 miles south of Makua) on Oahu where it forms thin brown laminae, and at Kekaha on Kauai where it makes up the bulk of the beachrock as it does also of the unconsolidated sand. Generally, however, the volcanic detritus comprises only a small percentage of the total grains. A summary of the composition of 33 samples of loose beach sand is given in Table 1. The source organisms were identified by shape and mineralogy of the grains: Foraminifera and calcareous red algae being calcite; *Halimeda* and madreporarian coral being aragonite. The mineral form was determined by use of a solution of cobalt nitrate (Meigen's solution) which stains aragonite violet and does not affect calcite. Some pelecypod and gastropod shells consist of both aragonite and calcite; thus some become stained and others are not affected. Accordingly, shells were identified only by remnants of flat or curved surfaces and occasionally by traces of decorative colors. These methods are more fully described in a report on sediments of Guam (Emery, in manuscript). Comparison of the composition of beach sands of the Hawaiian

[1] Contribution of Allan Hancock Foundation No. 167; contribution of Hawaii Marine Laboratory No. 76; published with the permission of the Director as paper No. 38 in the journal series of the Hawaiian Sugar Planters' Association. Manuscript received February 3, 1956.

[2] Department of Geology, University of Southern California and Experiment Station, Hawaiian Sugar Planters' Association, respectively.

Islands, Guam, and Bikini (Emery, Tracey, and Ladd, 1954: 38) shows the same major constituents in all the sands, but some differences in their relative proportions (Table 1). In the Hawaiian beach sands the most abundant constituent appears to be fragments of pelecypod and gastropod shells. Pieces of calcitic debris believed to be from calcareous red algae are next, followed closely by tests of Foraminifera, mainly *Amphistegina* with occasional *Marginopora*. Coral is relatively rare, and *Halimeda* debris was not found. The remaining material, called "fine debris" was too minute to permit visual identification of source organisms. Examination of polished sections of beachrock after similar staining showed the same assemblage of organisms, but percentage determinations were hampered by the presence of much calcitic cementing material.

Gravels that become cemented into beach conglomerate consist of wave-worn coral heads, large mollusk shells, pieces of basalt (Fig. 1), and reworked slabs of older beachrock (Fig. 2). Among the few places where beachrock contains volcanic gravels are areas near Kaena Point, Hauula, and Kapoho Point on Oahu, and Laau Point on Molokai. Silt and clay may also be present in beachrock

FIG. 1. Beachrock 3½ miles east of Kaena Point, Oahu. Lower layers contain many cobbles of volcanic rock.

FIG. 2. Beachrock at Keaau, Oahu, containing reworked slabs of older beachrock.

but are most conspicuous as distinct interbedded layers of alluvium or soil as at Keaau on Oahu (Fig. 3).

Near Laniloa Point and Kapoho Point on Oahu, and Nohili on Kauai, eolianite overlies beachrock near the high tide level. It may be distinguished by its finer grain size, steeper dip, and generally poorer cementation.

Cementation

The cementing material that binds sand into beachrock has been described by Ginsburg (1953), Emery, Tracey, and Ladd (1954: 43–45, 148, 149, pls. 22, 50, 52, 58), Illing (1954: 48, 70), and Ranson (1955) as consisting of calcite with some aragonite. Cementing material in beachrock from the Hawaiian Islands is similar to that described elsewhere, except that no aragonite was found. Failure of any of the pore fillings to become stained with Meigen solution indicates that all of it is calcite. Dr. Heinz Lowenstam of California Institute of Technology kindly confirmed the determination using a different stain.

Thin sections of beachrock from the site of Figure 4 show that pores of the upper layers are more completely filled than those of the lower layers (Table 2). Rinds, 30 to 60 μ thick and consisting of clear acicular calcite crystals about 4 μ thick, surround all the grains in the loose slab, surround less than 1 per cent of the grains in Layer G, and are absent in lower layers. The rest of the pore filling is brown calcite having randomly oriented grains that are more or less equidimensional and about 2 μ in diameter. If the pore filling found in the loose slab has passed through the stages of cementation represented by the lower layers, A to C, the rind of acicular calcite must be a secondary recrystallization feature.

The more complete filling of pores near the surface correlates with the common observation that beachrock is much harder at its exposed surface than at a depth of only an inch or two. An evaluation of the degree of cementation of beachrock at depth was made in the bay just west of Kahuku Point on Oahu. In this area, beachrock is especially well exposed (Fig. 4) because of retreat of the beach, probably due largely to sand removal by man. At least seven distinct layers of beachrock are present, some of which contain slabs reworked from older layers. Inspection of the exposed portions showed that the lower layers are less well cemented than the upper ones. The hardness of each layer was determined semiquantitatively by measuring the depth that a drill rod could be driven by 50 blows of a 16-pound sledge hammer (Fig. 5). Each layer was found to be slightly harder at its top surface than at depth. A deep hole, starting in Layer G, showed variations in driving rate correlative with the variations measured at the surface for the respective layers. The lesser resistance to driving found at depth also correlates with layers of poor cementation as judged from outcropping edges. Increased resistance at the bottom of the hole was probably due to entry into underlying reef rock. Similar results were obtained in another deep hole started in Layer C. Decrease in cementation at depth is also

FIG. 3. Whaleback of beachrock at Keaau, Oahu, with two interbedded layers of red alluvium.

FIG. 4. Layered beachrock dipping seaward at west side of small bay west of Kahuku Point, Oahu. Note reef rock on left against which beachrock abuts. Site of measurements diagrammed in Figure 5 is at left center.

well shown in the walls of a large drainage ditch cut through 5 feet of beachrock at Waieli on Kauai.

The characteristically poorer cementation at depth leads to ease of undercutting and movement of large slabs by waves. A slab near Kahuku Point on Oahu weighing probably 15 tons may have been overturned by the tsunami of 1946 (Fig. 6). Solution basins have just begun to form on the exposed bottom. Other areas having numerous loose slabs are Barbers Point, the beach a mile south of Waianae, and Makua on Oahu; Nohili on Kauai; and Hale o Lono on Molokai. At Nohili, erosion of soft material from beneath beachrock has allowed large slabs to slump to a position several feet below low tide level. The loose slabs are generally much harder than beachrock *in situ*, probably because cementation has proceeded from both top and bottom. When struck with a hammer the most firmly cemented slabs ring like gongs.

Surface

The surface of poorly cemented beachrock is rough, granular, and friable. That of well-cemented beachrock, however, is hard and becomes modified by at least four separate processes: polishing and film formation, discoloration by boring blue-green algae, biochemical solution, and abrasion.

Polishing of the surface is fairly common. In part, it is produced by continual washing of sheets of calcareous sand across the rock. It is present, therefore, chiefly where thin patchy sands overlie the beachrock. Cross sections of truncated shells, coral and other recognizable organic debris show on the surface. Polishing is supplemented by deposition of a film of very thinly laminated aragonite on the surface, which, as at Bikini (Emery, Tracey, and Ladd, 1954: 46, pls. 42, 43), fluoresces a bright reddish-orange under ultraviolet light. The film is especially well shown on beachrock at Nanakuli and on basalt at Mauna Lahilahi (about 1½ miles southeast of Makaha) on Oahu, on beachrock at Nohili on Kauai, and on beachrock at Kepuhi on Molokai. Especially at Nanakuli (Fig. 7) and Nohili the film appears to constitute a form of case-hardening that resists the development of solution basins. Some of the loose sands, such as Oahu sample 4 and Maui sample 1 of Table 1, are also highly polished and contain many grains which fluoresce. Illing (1954: 69) has noted similarly polished and coated sand grains on Bahaman beaches.

The second process that modifies the surface of hard beachrock is a darkening that is produced by activities of boring blue-green algae. In general the rock surface is a dull medium-to-dark gray, but at a few sites it is bright blue. Among the latter sites are Kawela Bay, Barbers Point, and Nanakuli on Oahu, and Kepuhi on Molokai. A piece of coral embedded in beachrock at Barbers Point was examined by Dr. Maxwell S. Doty of the University of Hawaii, who found *Entophysalis crustacea* and *Galothrix* living at the surface. For ¼ inch beneath the surface there was a succession of colored bands that Doty ascribed to natural chromatography of plant pigments and their decomposition products. The bands and their probable composition are as follows, from the surface inward:

blue—phycocynin
pink—phycoerythrin
clear
yellow—a carotinoid
green (thickest)—chlorophyll

Small pink or green spots at the sides of

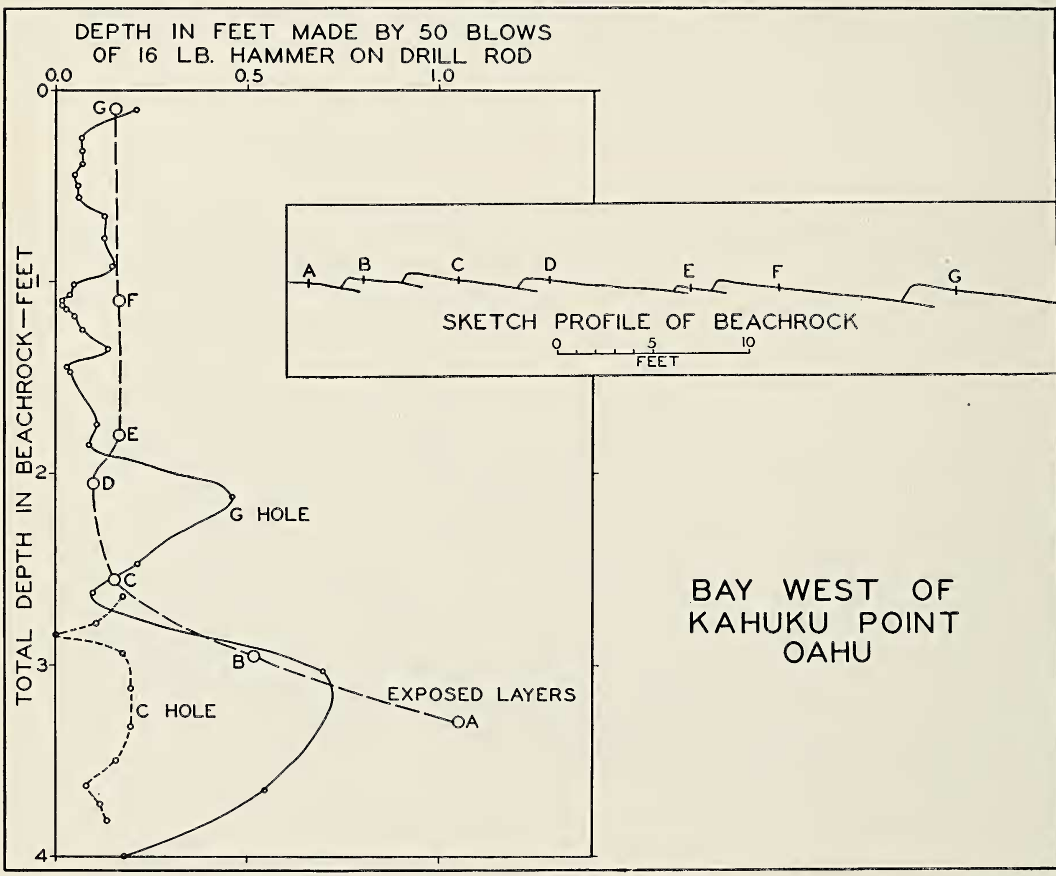

FIG. 5. Semiquantitative measurement of rock hardness, or degree of cementation, as determined by depth to which a drill rod could be driven by 50 blows of a sledge hammer. Line with long dashes shows measurements for exposed edges of layers. Solid line shows variation of hardness with depth in a hole driven vertically through all layers. Line with short dashes shows variation in a hole through three lowest layers.

TABLE 1
CHARACTERISTICS OF BEACH SANDS

LOCATION	MEDIAN DIAMETER MM.	SORTING COEFFICIENT	RESIDUE INSOLUBLE IN DILUTE HCl PER CENT BY WEIGHT	COMPOSITION OF CALCAREOUS PORTION (Per cent by Weight)					
				Foram-inifera	Shells	Fine debris	Halimeda debris	Coral	Calcareous algae
Oahu									
1. 5 mi. E Kaena Pt.	0.56	1.16	30	15	30	0	0	25	30
2. 1½ mi. W Mokuleia	0.98	1.29	5	25	35	0	0	10	30
3. Waimea Bay	0.73	1.33	5	40	40	0	0	5	15
4. 1 mi. E Waimea	2.10	1.50	0	2	55	0	0	5	38
5. ½ mi. S Laniloa Pt.	0.38	1.44	5	5	40	20	0	5	30
6. E side Kualoa Pt.	0.56	1.32	2	10	35	0	0	5	50
7. N Kaneohe Bay	0.18	1.69	99						
8. ¼ mi. N Kapoho Pt.	0.67	1.31	8	35	35	0	0	5	25
9. Kailua	0.58	1.54	1	15	30	0	0	5	50
10. 1 mi. S Kailua	0.22	1.22	45	10	25	50	0	5	10
11. Waimanalo	0.31	1.13	1	20	40	10	0	10	20
12. Hanauma Bay (E Koko Head)	0.63	1.47	98						
13. 2 mi. NW Koko Head	0.34	1.33	2	10	35	10	0	5	40
14. S side Diamond Head	0.62	1.29	30	10	30	0	0	20	40
15. W Ewa Beach	0.83	1.73	5	15	35	0	0	5	45
16. ½ mi. N Nanakuli	0.58	1.45	2	30	25	0	0	5	40
17. 1 mi. S Makaha	0.55	1.70	1	60	25	0	0	0	15
Kauai									
1. Haena	1.30		5	60	20	0	0	0	20
2. Hanalei Bay	0.20	1.53	80						
3. Kapaa	0.58	1.36	1	1	20	0	0	20	59
4. 3 mi. SE Waieli	0.28	1.43	0	5	15	0	0	25	55
5. Waieli	0.22	1.35	0	5	40	0	0	20	35
6. 4 mi. NE Nohili	0.40	1.30	10	5	15	0	0	35	45
Molokai									
1. 2 mi. S Kepuhi	0.45	1.19	5	50	20	0	0	0	30
2. Halawa	0.29	1.22	70	40	45	0	0	5	10
3. 5 mi. SW Cape Halawa	0.18	1.21	97						
4. 4 mi. E Kaunakakai	0.37	1.23	90	10	45	0	0	5	40
5. 1 mi. W Kaunakakai	0.23	1.61	75	10	65	0	0	10	15
Maui									
1. 2 mi. S Makena	0.41	1.50	1	60	20	5	0	0	15
2. 5 mi. S Kihei	0.19	1.16	10	10	40	40	0	0	10
3. 5 mi. SE Lahaina	0.23	1.20	95						
4. 2 mi. N Honokowai	0.76	1.49	40	50	35	0	0	0	15
5. Lower Paia	1.10		5	5	20	10	0	25	40
Hawaiian Islands average (33)	0.54	1.38	29	21	33	5	0	9	32
Guam average (11)	0.45	1.41	9	8	29	2	6	36	20
Bikini average (30)	0.87	1.51	0	26	9	4	2	28	31

FIG. 6. Large overturned slab of beachrock ½ mile east of Kahuku Point, Oahu, estimated to weigh about 15 tons. Solution basins have begun to form on the now exposed bottom.

FIG. 8. Solution basins in reef rock ½ mile north of Mauna Lahilahi, Oahu. The reef rock surface is seen to be typically rougher than that of beachrock.

boulders and in some solution basins are evidently the result of natural removal of the original, outer, colored layers. A brief description of these algae and their effect in coloring the surface of limestone has been given by Newhouse (1954). As pointed out by Cloud (1952: 28, 29) blue-green algae also invade the surface layer of loose beach sand, where they make a thin green layer and provide a weak form of cementation.

The remaining two surface processes, solution and abrasion, develop larger erosional features that have been well described by Wentworth (1944). Most common are basins

FIG. 7. Solution basins in beachrock having a case-hardened surface formed by deposition of a thin film of calcium carbonate at a place ½ mile north of Nanakuli, Oahu.

produced through solution of calcium carbonate by sea water trapped in pools (Fig. 8). This process is a complicated one and, as it is described rather fully by Revelle and Emery (in press), it will not be discussed here except to point out that solution basins are best developed and have sharp serrated edges in well-cemented beachrock (Layer G of Fig. 5, for example), they have rounded edges in moderately cemented beachrock (Layer F), and they do not exist in poorly cemented beachrock (Layers A to E). Their absence in poorly cemented beachrock is the result of high permeability that allows the pools to drain before much solution can occur. Solution also has produced water-level terraces that usually are divided by narrow low ridges into a series of rimmed pools (Fig. 9). These terraces and rimmed pools are common in reef rock of all the islands (Wentworth, 1939) but were noted in beachrock only at Nohili on Kauai, and at Hale o Lono on Molokai.

In contrast to the roughly circular form of solution basins, there are channels that are elongate and extend down the slope of the beachrock. These features have smooth, straight sides, and they quite evidently are produced by mechanical erosion along joints or other discontinuities through movement of sand or pebbles by wash of waves. Intermediate between the solution basins and the channels are potholes produced through mechanical abrasion by one or more cobbles that happen to become trapped in solution basins or other depressions in the beachrock.

Relationship to Beaches

In the Hawaiian Islands the maximum range of the tide is about 3 feet. Waves wash the beaches to a level ordinarily 2 or 3 feet higher than high tide. Little of the beachrock extends higher than the top of the wave-washed zone, but in several places it extends as much as 3 feet below low tide (west of Kahuku Point and at Hauula on Oahu; Nohili on Kauai; and Spreckelsville and Honokowai on Maui).

Most beachrock occurs on sandy beaches, usually with the same strike and dip as the layers of loose sand (Fig. 4). No beachrock was found at the ends of rocky points that project seaward between beaches, probably because of lack of sand.

In several places the beachrock, though at about the same height as the beach, has a different position in plan. The most conspicuous difference is shown by spits of beachrock that curve seaward away from the present beach, such as one at a point 1½ miles west of Mokuleia on Oahu (Fig. 10), and near Honokowai and at five places between Kahului and lower Paia on Maui.

FIG. 9. Rimmed terraces in beachrock at Nohili, Kauai. Note narrow anastomosing ridges that separate the pools of different levels. These consist of beachrock, showing that the rimmed terraces are erosional rather than built up by deposition. Beachrock extends several feet, at least, below low water.

FIG. 10. Curved spit of beachrock near Mokuleia, Oahu, showing that considerable retreat of beach sand in background has occurred since the time of cementation of the beachrock.

More common are "whalebacks," or anticline-like masses of beachrock located immediately off the beaches. In these the strike parallels the beach, but the layers dip seaward and landward on opposite sides. Such whalebacks were observed at Paumalu, south of Laniloa Point, Keaau (Fig. 3), Makua, and 4 miles east of Kaena Point on Oahu. An intermediate feature, massive seaward-dipping beachrock that forms a sort of offshore bar, occurs at Waieli and Nohili (Fig. 11) on Kauai. In many of these and other localities, the beach has obviously undergone large recent losses of sand owing either to natural causes, or to mining by man, or to both. Retreat of some beaches is also shown by recent undercutting of trees, by exposure of very soft beachrock at the back of beaches, and by historical records.

Along the coast of Oahu from 1 to 3 miles east of Kaena and at Diamond Head, beachrock is present but present-day beaches are either absent or are very small. East of Kaena, at Waimea, and on both sides of the point 2 miles south of Makaha, small patches of beachrock lie atop reef rock that has been raised 5 to 7 feet above mid-tide. These patches have sufficient horizontal extent to differentiate them from sands that have accumulated in small pockets of reefs as shown in the raised algal reefs at Waimea on Oahu. South of Laniloa Point and elsewhere, massive

FIG. 11. Bar-like ridge of seaward-dipping beachrock just beyond beach of loose sand at Nohili, Kauai.

beachrock overlies reef rock and reaches as much as 10 feet above mid-tide. At Kaena Point a Pleistocene shoreline 95 feet above sea level (Stearns, 1935) is marked both by reef rock and by about 13 feet of beachrock. Raised reef rock capped by beachrock was observed on none of the other three islands.

In summary, the position and attitude of most beachrock is closely accordant with present beaches, but some beachrock is discordant with present beaches owing to retreat of beaches, or to coastal elevation or submergence after the beachrock was formed.

DISTRIBUTION AND HYDROLOGY

General

The shores of Oahu were examined more thoroughly than those of Kauai, Molokai, and Maui, because beachrock is more abundant and the shores are more easily accessible. After experience had shown the rarity of beachrock at the ends of rocky points, most of the effort was spent on sandy bays between points. Altogether about 190 stations were made along the shores of Oahu, 100 on Kauai, 40 on Molokai, and 70 on Maui. Hawaii was not examined because beaches are rare and consist mostly of noncalcareous sand. Although Midway Island was not visited, Mr. J. A. Neff of the United States Fish and Wildlife Service (personal communication) reported the presence of slabby rock on Eastern Island that probably is beachrock. The results of the survey, based on measurements from the plottings on topographic maps, are presented in Table 3. Simplified plots for each of the four islands are given in Figures 12, 14, 16, and 17. Where no indication of beachrock or beach sand is given, the area was either not visited or was considered an impossible site for beachrock because of the absence of a sand beach.

It seems advantageous to describe very briefly the hydrology of the Hawaiian Islands because of the hypothesis that the development of beachrock is in some way controlled by the outflow of ground water through beaches. The hydrology of the four islands on which beachrock was studied is generalized in Figure 18.

The Hawaiian Islands consist of volcanic mountains built predominantly of basaltic lava flows and extending to heights of from 1,000 to 13,000 feet above sea level. Rainfall on these mountains is heavily influenced by the degree to which the moisture-laden winds, particularly the northeast trades, are forced upwards in their passage over or around them.

TABLE 2

COMPOSITION OF THIN-SECTIONS OF BEACHROCK SHOWN IN FIGURE 4

	PERCENTAGE OF AREA OF THIN-SECTION			PERCENTAGE OF ORIGINAL PORE AREA NOW FILLED
	Grains	Pore filling	Empty pores	
Loose slab	66	26	8	76
Layer G	57	33	10	77
Layer C	59	23	18	56
Layer B	56	15	29	35
Layer A	63	11	26	31

TABLE 3
Geographical Distribution of Beachrock in Hawaii

Coast	Total miles of coast	Miles of sandy beach examined	Miles of beachrock	Percentage beachrock of sandy beach examined	Percentage beachrock of total coast
Oahu					
Mokuleia to Paumalu..........	13.6	4.0	0.1	2	
Paumalu to Makahoa Pt........	10.4	6.0	4.9	82	
Makahoa Pt. to Mokapu Pen...	33.6	20.8	1.0	5	
Mokapu Peninsula............	11.2	1.7	1.5	88	
Kapoho Pt. to Waikiki Beach...	31.4	16.5	1.3	8	
Waikiki Beach to Pearl Harbor..	19.5	0.0	0.0?	0	
Pearl Harbor to Mokuleia......	42.5	24.0	12.0	50	
Total....................	162.2	72.0	20.8	29	13
Kauai					
3 miles NE Nohili to Kealia....	47.4	10.2	2.6	25	
Kealia to Waimea.............	46.5	12.4	2.6	21	
Waimea to 3 miles NE Nohili...	16.6	13.0	2.6	20	
Total....................	110.5	35.6	7.8	22	7
Molokai					
4 miles E Hale o Lono to Kepuhi	15.2	7.5	4.8	64	
Kepuhi to Cape Halawa........	50.9	0.0	0.0?	0	
Cape Halawa to 4 miles E Hale o Lono....................	38.2	9.0	0.0	0	
Total....................	104.3	16.5	4.8	29	5
Maui					
Maliko Bay to Makena........	84.2	0.0	0.0?	0	
Makena to Lahaina............	31.5	10.5	0.0	0	
Lahaina to Kahului............	34.0	7.3	1.6	22	
Kahului to Maliko Bay........	11.1	6.6	1.7	26	
Total....................	160.9	24.4	3.3	14	2
Grand Total..............	537.9	148.5	36.7	25	7

In areas of maximum rainfall, located on the windward slopes of the higher mountains and at the crests of the lower mountains, the mean annual rainfall is commonly in excess of 200 inches per year. On the leeward slopes the rainfall is generally much less than on the windward slopes, and on the lower parts of leeward slopes the mean annual rainfall may be less than 20 inches per year. The wide geographic variation in rainfall creates wide variations in both surface-water and ground-water resources.

There is surface runoff from all except the youngest terrains formed by fresh porous lava flows. The courses of the streams are, however, so steep and short that the runoff alone creates flashy and, in the low rainfall areas, infrequent flows. However, many streams have cut valleys sufficiently deep to tap ground-water bodies that are perched on layers of comparatively low permeability interbedded in the generally highly pervious lava flows or are impounded between intrusive bodies in the central areas of the volcanoes, and have thereby developed perennial flows from springs. Much of the portion of the rainfall that infiltrates the surface does not reappear in high-level springs, but descends

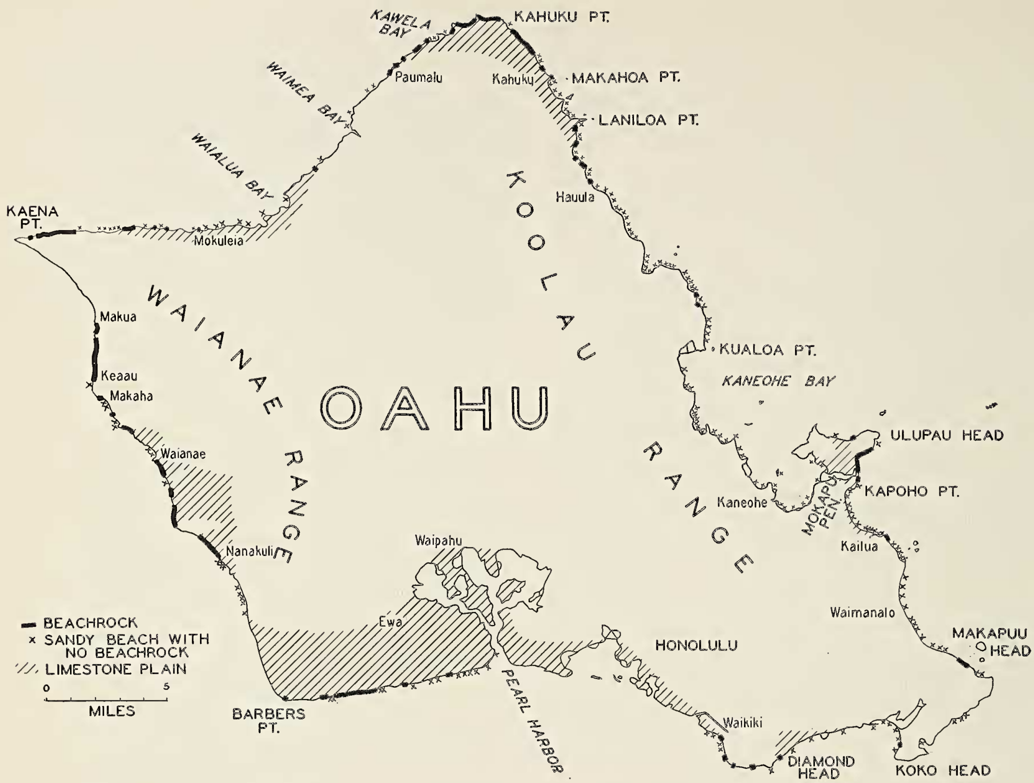

FIG. 12. Distribution of beachrock on Oahu.

to sea level in the lavas where it accumulates to form lenses of fresh water floating on the denser salt water penetrating from the sea. The thickness and freshness of these lenses depends in part on the amount of infiltration they receive and in part on the ease with which the water in them can drain seaward. Where the lavas crop out at the coast line there is generally easy outflow, and the lenses are thin. Particularly on the older islands, however, there may be extensive coastal plains underlain by prisms of sediments, partly coral and other limestones of generally high permeability, but also partly muddy sediments whose permeability is much lower than that of the lavas. Such sedimentary prisms constitute barriers restricting or diverting the ground-water outflow and causing the fresh-water lenses to be thicker in the bedrock behind such coastal plains.

Oahu

The northwestern coast of Oahu, from Mokuleia to Paumalu, is low, and two of the island's largest rivers enter at Waialua and Waimea Bays. Ground water stands comparatively high in the bedrock lavas behind the coast, except in a stretch a couple of miles each side of Waimea Bay, its height indicating that its drainage seaward is restricted by the sediments that make up the coastal plain. Springs create swamps on parts of the plain, and some of the drainage of these swamps may take place diffusely through the beaches, though the largest outflows are probably by way of the rivers and a few springs at or below sea level. Beachrock was found at only one locality (Fig. 12), not near a spring, where it dips seaward in the wave-washed zone.

The northern shore, backed by a wide limestone plain from Paumalu to Makahoa Point, is characterized by an almost continuous strip of beachrock interrupted by a few sand-free projecting points. Within the bays, beachrock forms seaward-dipping strata as much as 4 feet thick atop reef rock (Fig. 4), though locally the beachrock is so thin that reef rock projects through it. The contact between reef rock and beachrock is commonly near the mid-tide level (Fig. 13). In most of this area the beachrock is in the wave-washed zone; but just east of Kahuku Point it rests on reef rock reaching to 5 feet above mid-tide, and just west of Kahuku Point it extends a foot or two below low tide. As it does farther west, the ground water stands high in the bedrock lavas back of this northern shore, and again leakage from the bedrock creates swamps and ponds in the limestone plain. The points of seaward drainage from these swamps are not known, but there are no conspicuous springs at or above sea level. No perennial streams reach the shore in this stretch of the coast.

Eastward from Makahoa Point the coastal plain narrows and is broken by stretches where bedrock lavas crop out at sea level. At such places there must be outflow of ground water, and at a few places there are visible springs at or just above sea level. The mountain rainfall increases eastward, the valleys are more deeply incised, and a number of perennial streams reach the shore between Makahoa Point and the base of Mokapu Peninsula.

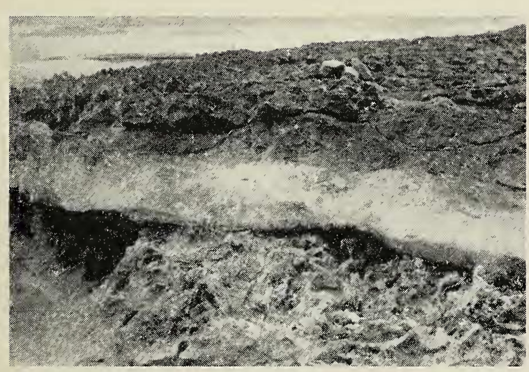

Fig. 13. Contact of beachrock atop reef rock near mid-tide level at a place one mile east of Kahuku Point, Oahu.

This shore contains little beachrock. Most of that which is present occurs between Laniloa Point and Hauula, where it forms thin seaward-dipping beds in the wave-washed zone except in the middle of the area where it rises from below mid-tide to 8 feet above mid-tide and is overlain by hard eolianite. About 1 mile south of Laniloa Point poorly cemented eolianite occurs at the base of a 10-foot cliff cut in dune sand. Beachrock was not found within Kaneohe Bay, an area of dilute sea water with many fish ponds along the shore. Islands within the bay are free of beachrock, perhaps because of the absence of loose sand, and, in the case of Coconut Island, because of artificial shores.

The Mokapu Peninsula consists of a core of late, relatively impervious, volcanic rocks and a surrounding limestone plain. The rainfall is low and there are no streams and probably very little ground water. Along shores on the eastern side of the peninsula there are extensive and massive beds of beachrock dipping seaward. Most of the beds are in the wave-washed zone, but near Ulupau Head some of the beachrock atop reef rock reaches to 10 feet above mid-tide. At Kapoho Point the reef rock is overlain by eolianite that has been truncated and drilled by potholes that later became filled by alluvium.

Over the eastern end of Oahu the rainfall decreases again, and no perennial streams drain to the coast east of Waimanalo and Honolulu. The permeability of even the bedrock is low in Kailua and Waimanalo on the windward side of the island, and although ground water stands relatively high in places, the amount of flow is probably not great. In the Honolulu area there are well-developed ground-water bodies in the bedrock whose seaward drainage is so restricted by coastal-plain sediments that most of the outflow probably takes place laterally to the coast through a limestone plain east of Diamond Head, and to Pearl Harbor, at the head of which there are very large springs. Makapuu Head is a mass of bedrock lavas cut into cliffs at sea level. The rainfall is so low there, however, that there is probably very little ground water. Koko Head and Diamond Head are pyroclastic cones of low permeability and probably contain negligible ground water.

The shore of the southeastern part of Oahu from Kapoho Point to Waikiki Beach is mostly free of beachrock, although sandy beaches are abundant. Beachrock occurs in small thin patches near Kailua, northwest of Makapuu Head, near Koko Head, and around Diamond Head. At Diamond Head it lies atop a tuff terrace and beneath talus and eolianite in areas now free of loose beach sand. In all the areas except the one northwest of Makapuu Head, the beachrock is in the wave-washed zone; at this one place, a 1-foot layer of beachrock atop reef rock reaches to 8 feet above mid-tide.

Between Waikiki and Barbers Point, leakage from well-developed ground-water bodies in the bedrock lavas and seepage from streams have created thin fresh-water lenses in, and swampy spots on, the surface of the coastal plain, much of which is composed of limestone. No notable shoreline springs are known, however, except the Pearl Harbor springs previously mentioned, which represent drainage direct from the bedrock. From Barbers Point northwest to Makaha the bedrock ground-water bodies are less well developed because the rainfall is much lower. There are still thin lenses of ground water in the coastal-plain sediments as far as Makaha, at least, but again no notable shoreline springs are known. No perennial streams reach the shore. The Kaena Point area at the western end of the island is very dry.

Shores between Waikiki Beach and the entrance of Pearl Harbor are so altered by man that they were not investigated. Beginning at the entrance of Pearl Harbor and extending around Barbers Point and Kaena Point to Mokuleia, the coast is dominated by beachrock except at projecting sand-free points. Between the entrance of Pearl Harbor and Barbers Point beachrock alternates with loose sand, with a general westerly increase in abundance of beachrock. Where present, the beachrock is restricted to the wave-washed zone. The 4-mile stretch of coast northwest of Barbers Point and the 5-mile section southeast of Kaena Point were not visited because of the lack of roads. Lava reaches the shore most of the way in the latter stretch (Wentworth, 1938: 8). Along most of the rest of the Waianae shore, beachrock is almost continuous except on the projecting points. The beachrock is almost equally divided between massive beds in the wave-washed zone (Fig. 2) and thin patches atop reef rock to heights of 5 to 8 feet above mid-tide. At Keaau it is interbedded with alluvium (Fig. 3). About half of the shore of abundant beachrock is backed by a wide limestone plain (Fig. 12), but in the northern part, from Keaau to Makua, only the beach separates the lavas from the sea.

Kauai

The island of Kauai has had a more complex structural history than the other Hawaiian Islands. As a consequence, the permeability of its rocks is in general lower and the amount of ground water smaller in relation to surface water.

The western half of the northern coast, from 3 miles northeast of Nohili nearly to Haena Point, consists of cliffs cut into bedrock lavas and is inaccessible except by foot or boat. Sand beaches are rare and no beachrock has been found.

Most of the rest of the northern coast, the eastern coast, and the southern coast to Waimea, consist of gentle slopes or low cliffs cut in relatively late lavas of generally low permeability. Numerous perennial streams reach the sea, and beaches at their mouths are common. In addition, there is a narrow coastal plain extending with minor breaks for about 5 miles south from Kapaa. Southwest of Nawiliwili Bay for 5 miles the coast consists of cliffs similar to those of the northwestern

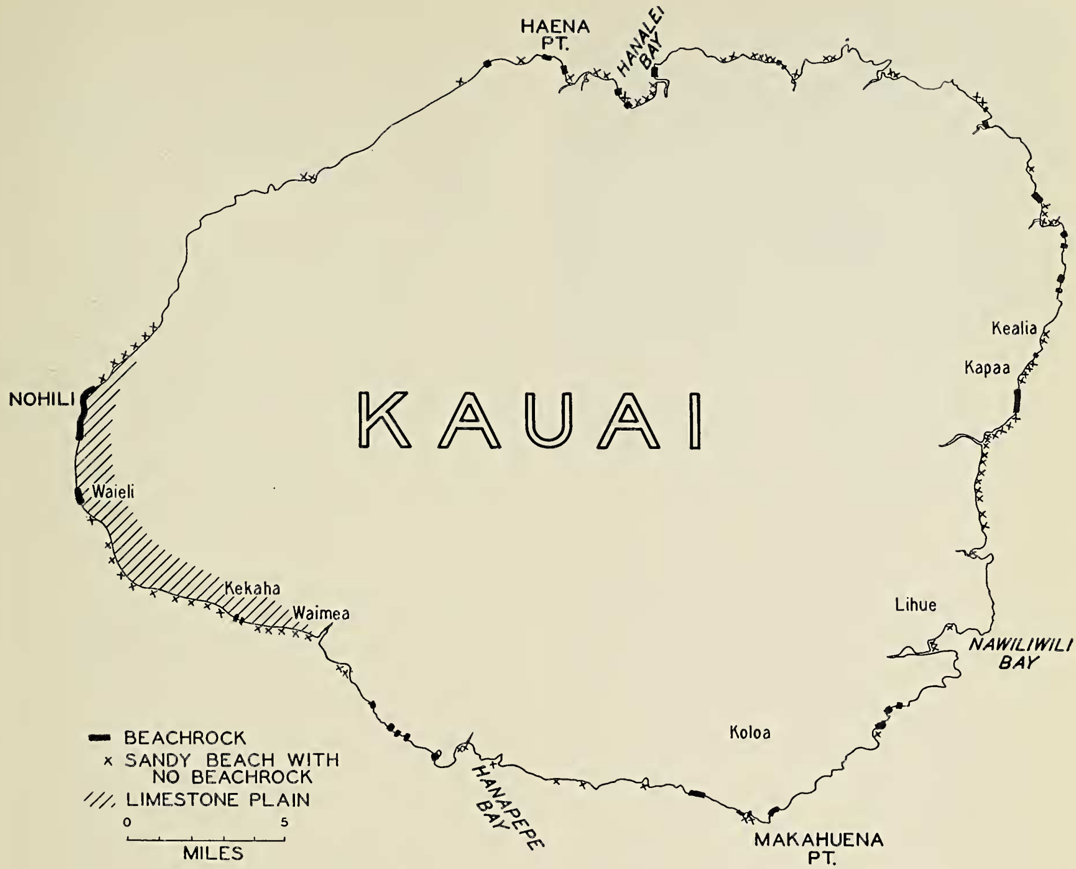

FIG. 14. Distribution of beachrock on Kauai.

coast. Beachrock is present in many small patches along these coasts, none more than 0.3 mile long (Fig. 14) and all consisting of thin seaward-dipping beds in the wave-washed zone. About a half dozen occurrences between Haena and Kealia are at the mouths of small to moderately large streams, in contrast with the absence of beachrock in such places on Oahu.

The western coast, between Waimea and a point 3 miles northeast of Nohili, is backed by a limestone plain that reaches a width of 2 miles. The surface of the plain was once largely covered by a swamp fed by intermittent streams and by leakage of ground water from the bedrock lavas in cliffs back of the plain, but the swamp has been artificially drained. Along the seaward margin is a wide high sandy beach locally backed by dunes. A local fisherman reported that the northernmost part of the beach has become considerably wider in the past few years and in this area no beachrock is exposed. The escape of fresh ground water through the beach sand is notable 3 miles northeast of Nohili, where the coastal plain pinches so that the beach rests directly against the bedrock cliff. In the middle of the area, at Nohili, there is a 2-mile exposure of massive beachrock (Fig. 11) reaching about 4 feet above mid-tide and at least 3 feet and possibly 8 feet below mid-tide. The uncertainty is due to slumping of large blocks of the beachrock due to the erosion of some undetermined softer material

FIG. 15. Beachrock at Nohili, Kauai, showing solution basins having rounded and smoothed surfaces believed to indicate modification of ordinary sharp-edged solution basins during a period of burial under loose beach sand followed by exhumation.

underlying it. The slumped blocks range up to 30 by 15 by 5 feet. A shorter exposure of beachrock at Waieli has been transected by a drainage ditch that reveals progressive decrease of cementation of the beachrock at depth. Some of this beachrock has a rounded and smoothed surface (Fig. 15), unlike beachrock elsewhere which is undergoing active solution. This is presumed to indicate a former exposure of the beachrock followed by burial under thick sand, and finally exhumation by recent retreat of the beach. Judging from the massive nature of beachrock at both Nohili and Waieli, it seems likely that this entire section of the western coast is underlain by beachrock that now is exposed only where recent retreat of beach sand has occurred. Retreat of the beach has also exposed very poorly cemented beachrock and eolianite landward of the main mass of beachrock at Nohili.

Molokai

The eastern part of Molokai has a high rainfall, and is well drained by both surface streams and ground-water flow. Particularly along the southern coast a few miles south of Cape Halawa to a few miles west of Kaunakakai the escape of ground water at sea level is notable. The western part is very dry with no perennial streams and only brackish ground water.

Beachrock on Molokai is confined to the southwestern and western coasts, from a point 2 miles east of Hale o Lono to Kepuhi (Fig. 16). A 4-mile continuous exposure of beachrock, the longest seen in the islands, centers at Hale o Lono. Within the wave-washed zone and seaward-dipping, most of this beachrock is slabby and some of it has been quarried for building purposes. In the area north of Laau Point beachrock is slabby like that at Hale o Lono, but it reaches to 8 feet above mid-tide. The bay near Kepuhi contains some of the most massive beachrock seen in the islands, reaching from below mid-tide to 10 feet above it. The surface is highly polished

FIG. 16. Distribution of beachrock on Molokai.

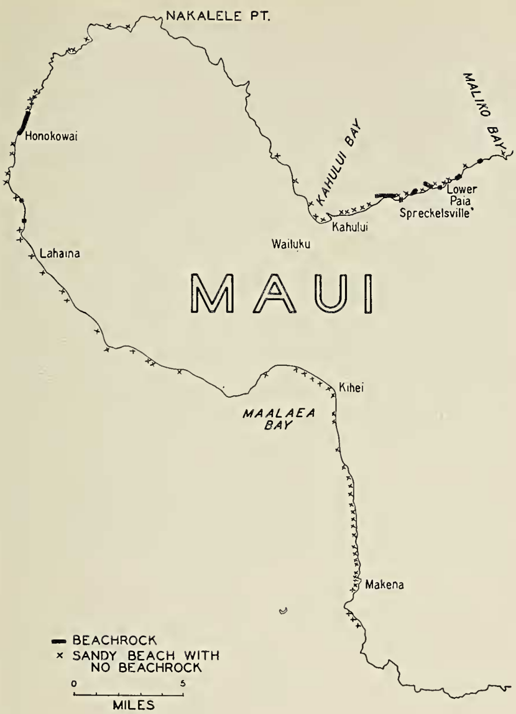

FIG. 17. Distribution of beachrock on Maui.

and locally is discolored by blue-green algae. Elongate erosional channels are well developed.

From Kepuhi around Ilio Point to Cape Halawa, the coast is precipitous with only two sandy beaches. At one of these places, Kalaupapa, possible but uncertain beachrock was noted from a vantage point at the top of the high cliff about 2 miles away. This is believed to be the only possible site of beachrock along the entire northern coast of Molokai. The southern coast from Cape Halawa to Hale o Lono was examined closely without finding any trace of beachrock. Scattered along almost the entire shore are artificial fish ponds in which mullet and other brackish-water fish are cultivated. Muddy sediments have accumulated along the more protected parts of this shore. *Ulva*, or sea lettuce, is very abundant along the shores, forming local drifts about a foot thick.

Maui

Less beachrock was found on Maui than on any of the other islands examined, a total of 3.3 miles of shoreline length (Fig. 17). The absence of sand beaches around most of East Maui, from Maliko Bay to a point 2 miles south of Makena, means that the presence of beachrock is very unlikely, so the available field time was concentrated in more favorable areas.

No perennial streams reach the shores of East Maui from Kahului Bay to Maliko Bay except at Maliko, nor from Maalaea Bay to far east of Makena. However, east of the two bays, the bedrock lavas extend to the shores with only a thin discontinuous mantle of beaches, so that ground water escapes easily at or near sea level. On the southern coast the ground water is brackish and probably not plentiful, but there must be a substantial outflow along the northern coast. It is noteworthy that there is beachrock on the northern coast, but none on the plentiful beaches of the southern coast. The beachrock on the northern coast consists of an interesting series of five spits and bars, between Spreckelsville and Lower Paia, and occurrences in the wave-washed zone in two bays northeast of Lower Paia. In one of these bays and at the small point north of Spreckelsville beachrock overlies red soil, and at the latter site it also directly overlies a basaltic flow in places. More beachrock is shown in offshore positions in this area than elsewhere in the islands, and the remnants are also farther offshore, suggesting that retreat of sand beaches has been great. Recent retreat is also indicated by undercutting of trees and by historical records. Some of the sand may have been transported to the southwest and added to the beach near Kahului where no beachrock could be found, but additional sand has been removed for construction purposes. One of the beaches at Spreckelsville was covered with drifts of *Ulva*.

Narrow coastal plains, in which no beachrock was found, front Maalaea Bay and Kahului Bay. Cliffs form the coasts of West Maui for 3 miles west of Maalaea Bay on the south, and from Kahului Bay around Nakalele Point nearly to Honokowai on the north. The few sandy beaches on these shores do not contain beachrock.

The rest of the coast, on the west and southwest, consists of a narrow coastal plain. Judging from the low and fairly uniform height of the ground water in the bedrock back of the coastal plain, there must be fairly plentiful points of ground-water escape, but none are known at or above sea level. South of Lahaina there are no exposures of beachrock, but 2 miles to the north there is a small outcrop and another mile farther north there are loose slabs of beachrock. Near Honokowai beachrock in the wave-washed zone extends along more than a mile of shore, in some sections forming a spit or bar 20 to 50 feet offshore of the present beach. Locally, two bars are present. Along some of this shore, recent retreat of a 10-foot cliff of alluvium is indicated by undercutting of large trees, and this retreat is in part responsible for exposing some beachrock. Except for two small outcrops just north of Mahinahina Point, a mile north of Honokowai, beachrock is absent around the rest of West Maui.

AGE

In most areas the beachrock could have been formed very recently, even within the

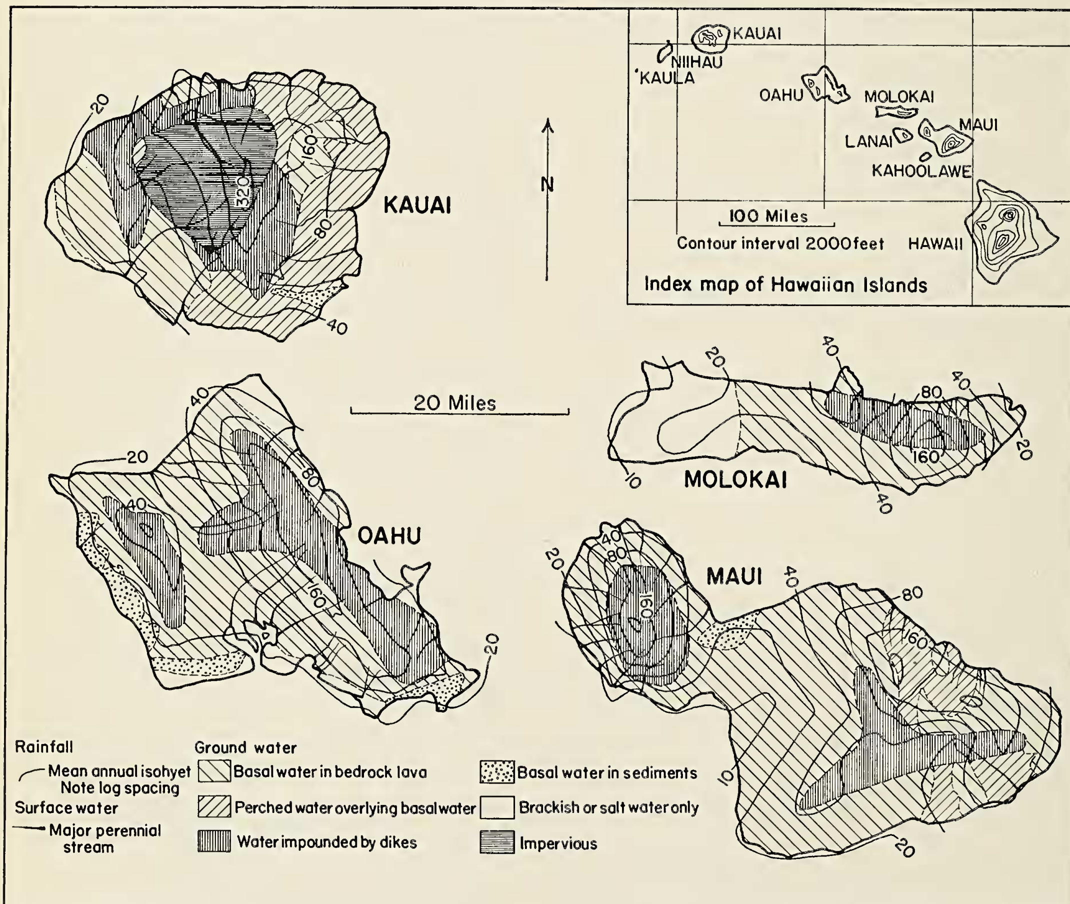

FIG. 18. Map showing hydrology of Kauai, Oahu, Molokai, and Maui.

last decade. A recent age is suggested by the common restriction of the beachrock to positions within the wave-washed zone and to the similarity of its strike and dip to those of the present beach. A somewhat greater age in other places may be indicated by differences in the positions of the beachrock and the present beach (i.e., presence of beachrock spits and whalebacks) indicating retreat of the beach since the beachrock was formed. A locally greater age is also indicated by interbedding of beachrock with other materials. Alluvium is interbedded or overlies beachrock at Waianae and Keaau on Oahu. Near Lower Paia on Maui beachrock rests on red soil that is now intertidal in position.

Some beachrock must be older, and of a greater age than nearby intertidal beachrock, for on Oahu it occurs on raised reef rock as much as 10 feet above present sea level. Elsewhere, ½ and 2½ miles south of Laniloa Point and at Diamond Head on Oahu, beachrock is overlain by eolianite, which at Diamond Head is itself overlain by talus. The greatest age of all, Pleistocene, is indicated for beachrock on the 95-foot Kaena terrace of Oahu.

In summary, beachrock in the Hawaiian Islands may be of three different ages: modern to a few thousand years old (wave-washed zone); probably several to many thousand years old (on raised reef rock and/or overlain by alluvium or eolianite); and Pleistocene age (Kaena terrace). In addition, it is evident that even the youngest of these three ages represents not a single stage of cementation, but rather several to many separate stages. Repeated stages of cementation are well shown by the common presence of reworked beachrock slabs incorporated in later layers and by truncation of earlier layers by later ones.

ECONOMIC VALUE

Beachrock of many tropical islands has long been used for minor construction purposes, such as grave markers and flagstones. Some has also been used to make "flint" artifacts. Slabs of beachrock were quarried from near Hale o Lono on Molokai and transported to Honolulu for decorative use in buildings. It has also been quarried near Barbers Point on Oahu, according to Stearns (1939). Many other beaches are capable of supplying such slabs. From still other localities solid dimension stone, 2 to 4 feet in smallest dimension, can be obtained. Among the best of these localities are: bays on both sides of Kahuku Point, two areas just south of Laniloa Point, and two areas just south of Waianae on Oahu; at Waieli and Nohili on Kauai; and at Kepuhi on Molokai. The economic value, however, is not great because the cut stone probably would have an appearance very similar to concrete made from loose beach sand.

Beachrock has also been found to constitute the best source, on atolls, of aggregate for concrete. The rock is quarried, crushed, screened, and mixed with cement and sea water to form a good grade of concrete (Narver, 1954).

ORIGIN

The main purpose of this investigation was to discover, if possible, the origin of beachrock—at least of the beachrock in the Hawaiian Islands. Altogether, beachrock was noted along approximately 37 miles of the shores, but in such a variety of environments that it is difficult to isolate the least common denominator, or most probable controlling factor.

Absence of beachrock at the ends of points and other areas where loose beach sand is not now present, nor probably ever was present, leads to the obvious conclusion that loose beach sand must be available if beachrock is to form. Beyond this point, generalizations appear to have many exceptions.

Before making the present study, the authors recognized that beachrock is abundant around islets of atolls and relatively rare around high islands of moderately great rainfall such as Guam. The hypothesis was developed that beachrock occurs where the interstitial water of beaches is sea water, which is already saturated with calcium carbonate, and that it should be absent where the interstices are occupied by ground water that has passed only through volcanic rocks and is presumably not saturated with calcium carbonate. In addition, beachrock should be present where the beach contains ground water that has escaped from a wide limestone plain and thus contains a high percentage of calcium carbonate. The basis for this hypothesis is that water that is left in the beach by a falling tide or that rises by capillarity through the beach sand largely evaporates near the sand surface. Any salts originally dissolved in the water are precipitated in the sand where they serve as a cement (Emery and Foster, 1948). Readily soluble salts such as sodium chloride are removed by the next high tide, but salts such as calcium carbonate may remain to form a more permanent cement. In addition, the heating of the beach by the sun during the day tends to reduce the solubility of CO_2 in the interstitial water close to the surface, so that its pH rises. If the water is initially near saturation, calcium carbonate is precipitated (Emery, Tracey, and Ladd, 1954: 45–46). Because sea water contains more calcium carbonate than most ground waters, it seems reasonable to expect that beach sands would be cemented into beachrock more easily where sea water is evaporated than where only fresh water containing little calcium carbonate is evaporated.

On Oahu the hypothesis appears to be supported generally by field data. Beachrock is abundant along the western coast where the rainfall is low and on Mokapu Peninsula, also a low rainfall locality. Conductimetric tests show that interstitial beach water in these areas is sea water; therefore, it is probable that little ground water escapes through these beaches. One of the chief areas of beachrock on Oahu is the northern coast around Kahuku Point, an area where considerable quantities of fresh water escape and where conductimetric and titration tests showed that ground water is associated with beachrock. Titration of four water samples from the bottom of the deepest hole of Figure 5, of three from the loose beach sand, and of three from the ocean water atop the reef flat, yielded average chlorinity values of 2.50, 3.58, and 19.14 parts per thousand, respectively. Comparison of the calcium and chloride concentrations (Table 4) shows that both ions are less abundant in water collected from the hole in beachrock than in sea water, but that the calcium concentration with respect to chloride is about twice as great as in sea water. This high ratio of calcium to chloride in the ground water means that much of the calcium must have been derived from the rocks through which the water passed. Some additional support for the hypothesis can be obtained by consideration of the areas where beachrock is absent. Very little beachrock occurs along most of the eastern coast of Oahu where high rainfall leads to escape of large amounts of surface and ground water. No beachrock whatever is known in Kaneohe Bay, where sea water was found to be diluted

TABLE 4
COMPOSITION OF WATERS

	CALCIUM ppm	CHLORIDE ppm	CA/CL	SOURCE OF DATA
Hole through beachrock of Figure 5	144	2,610	0.0552	USC analysis by Dr. Wilson Orr
Sea water (general)	400	18,980	0.02106	Sverdrup, Johnson, and Fleming (1942: 173)
Sea water (Hanauma Bay)	507	19,681*	0.0258	Stearns and Vaksvik (1935: 361)

* Includes nitrate.

by fresh watei escaping from volcanic rocks or flowing atop an alluvial plain.

On Molokai the distribution of beachrock fits the hypothesis even better. Beachrock is well developed along the western and southwestern shores, where escape of ground water is probably small because the rainfall is low. Beachrock is absent along the rest of the southern shore. This coast, though itself low in rainfall, receives much ground water from the main ridge of East Molokai which has a high rainfall. Because of the considerable escape of ground water, the nearshore sea water has been diluted, especially in the large artificial fish ponds that were built in ancient times. Brackish water in these ponds supports a crop of mullet, a fish that prefers fresh or brackish water (Hiatt, 1944). In the same area *Ulva*, sea lettuce, is prolific (Abbott, 1947), suggesting that it too prefers dilute sea water. The only other areas of abundant fish ponds are along Kaneohe Bay and the southeastern shore of Oahu, and here also beachrock is absent.

On Maui a reversed situation exists. Beachrock is absent or rare around the leeward coast of low rainfall and probably little ground water, but abundant near Lower Paia where considerable dilution by ground water is known. In this area the ground water comes directly from the volcanic rocks to the beach, as it does along the southern shore of Molokai. Thus, on Maui the distribution of beachrock does not fit the original hypothesis.

On Kauai, as on Maui, beachrock appears to be independent of the kind of interstitial water. The most extensive area of beachrock is the western alluvial coast, a situation similar to the dry western coast of Oahu where beachrock is abundant. However, beachrock also occurs in small patches around other shores of Kauai, and some of these patches lie at the mouths of perennial streams.

Altogether, the evidence from distribution shows no unequivocal preference of beachrock for beaches having interstitial water composed of sea water, ground water from limestone plains, or ground water from volcanic rocks. If the nature of the interstitial water were a dominant control, we must be prepared to say either that areas which now contribute much ground water directly from volcanic rocks formerly contributed little ground water, and that beachrock in those areas was formed during the past, or that details in the pattern of the ground-water flow, not predictable except possibly by a study more intensive than that reported, lead to important variations in the nature of the interstitial water in the beaches. The first conclusion does not appear to be reasonable, and the second begs the question. We must look, therefore, for other possible explanations or for supplementary factors.

One such explanation was proposed by Cloud (1952) who suggested that blue-green algae, known to live in the top quarter-inch of some beach sands, may cement the sand through their biochemical activities. Cementation of individual layers, 2 feet or more thick, appears to be a fatal objection, because the algae are probably restricted to the topmost fraction of an inch in order to receive enough sunlight for photosynthetic activities. Another possible explanation proposed by Nesteroff (1955: 33) and Ranson (1955) is that amorphous calcium carbonate is deposited between the sand grains by the action of bacteria living in organic material deposited with the sand. However, there seems to be no evidence of the presence of large amounts of organic material in the Hawaiian beachrock and the organic content of the sand is extremely low (Oahu samples 1, 5, 8, 15, and 16 of Table 1 have organic carbon percentages of only 0.10, 0.16, 0.14, 0.22, and 0.09, respectively).

Merrin (1955), who studied beachrock in Puerto Rico, proposed that beachrock is restricted to areas of stable beaches; however, many of the Hawaiian beaches having beachrock are known to undergo large changes seasonally and because of storms. In fact, some of the areas of beachrock on Kauai shown by Figure 14 were covered by sand at the time of our mapping and were discovered by Dr. Douglas Inman of Scripps Institution of Oceanography during a later visit.

In short, although beachrock is abundant in the Hawaiian Islands and elsewhere, we do not know how it forms. Mapping its distribution is not by itself a sufficient source of data to solve the problem of origin. Perhaps the making of many additional chemical analyses of interstitial waters of beaches would be a helpful supplement to mapping.

REFERENCES

ABBOTT, I. A. 1947. Brackish-water algae from the Hawaiian Islands. *Pacific Sci.* 1 (4): 193–214.

CLOUD, P. E. 1952. Preliminary report on geology and marine environments of Onotoa Atoll, Gilbert Islands. *Atoll Res. Bul.* No. 12: 1–73.

EMERY, K. O. In press. Marine geology of Guam. *U. S. Geol. Survey, Prof. Paper.*

EMERY, K. O., and J. F. FOSTER. 1948. Water tables in marine beaches. *Jour. Mar. Res.* 7:644–654.

EMERY, K. O., J. I. TRACEY, JR., and H. S. LADD. 1954. Geology of Bikini and nearby atolls. *U. S. Geol. Survey, Prof. Paper* 260–A: 1–265.

GARDINER, J. S. 1931. *Coral reefs and atolls.* xiii + 181 pp., 15 pls., 4 maps. Macmillan Co., New York.

GINSBURG, R. N. 1953. Beachrock in south Florida. *Jour. Sed. Petrology* 23: 85–92.

HIATT, R. W. 1944. Food-chains and the food cycle in Hawaiian fish ponds, II Biotic interaction. *Amer. Fish. Soc., Trans.* 74: 262–280.

ILLING, L. V. 1954. Bahaman calcareous sands. *Amer. Assoc. Petrol. Geol., Bul.* 38: 1–95.

MERRIN, S. 1955. Beachrock in northeastern Puerto Rico. *First Carribean Geol. Congress, Antigua, British West Indies.* 15 pp. [mimeographed.]

NARVER, D. L. 1954. Good concrete made with coral and sea water. *Civ. Engin.* 24: 654–658, 725–728.

NESTEROFF, W. D. 1955. Les récifs coralliens du Banc Farsan Nord (Mer Rouge). *Résult. Sci. des Campagnes de la "Calypso."* 1: 1–53.

NEWHOUSE, J. 1954. Ecological and floristic notes on the Myxophyta of Raroia. *Atoll Res. Bul.* No. 33 (2): 42–54.

RANSON, G. 1955. La consolidation des sédiments calcaires dans les régions tropicales. *[Paris] Acad. des Sciences, Compt. Rend.* 240: 640–642.

REVELLE, R., and K. O. Emery. In press. Chemical erosion of beach rock and exposed reef. *U. S. Geol. Survey, Prof. Paper* 160–W.

STEARNS, H. T. 1935. Pleistocene shore-lines on the islands of Oahu and Maui, Hawaii. *Geol. Soc. Amer. Bul.* 46: 1927–1956.

——— 1939. *Geologic map and guide of the Island of Oahu, Hawaii.* x + 76 pp., 23 figs., 1 map. Ter. of Hawaii, Div. Hydrog. Bul. 2. Honolulu.

STEARNS, H. T., and K. N. VAKSVIK. 1935. *Geology and ground-water resources of the Island of Oahu, Hawaii.* xx + 479 pp., 33 pls., 34 figs. Ter. of Hawaii, Div. Hydrog. Bul. 1. Honolulu.

SVERDRUP, H. U., M. W. JOHNSON, and R. H. FLEMING. 1942. *The Oceans.* x + 1087 pp., 265 figs., 7 charts. Prentice-Hall Inc., New York.

WENTWORTH, C. K. 1938. Marine bench-forming processes, I. Water-level weathering. *Jour. Geomorphol.* 1: 6–32.

——— 1939. Marine bench-forming processes, II. Solution benching. *Jour. Geomorphol.* 2: 3–26.

——— 1944. Potholes, pits, and pans: Subaerial and marine. *Jour. Geol.* 52: 117–130.